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Ordovician reef and mound evolution: The Baltoscandian picture

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Original Article

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Short title: Baltic reefs

Abstract:
Widespread growth of reefs formed by a framework of biogenic constructors and of frame-lacking carbonate mounds started on Baltica during the Ordovician. Previously, Ordovician reef and mound development on Baltica was considered to be sporadic and local. A review of all known bioherm localities across the Baltic Basin reveals a more consistent pattern. Ordovician bioherms grew in a wide E/W stretching belt across the Baltic Basin and occur in several places in Norway. Substantial reef development began simultaneously across the region during the late Sandbian / early Katian boundary interval and climaxed during the late Katian Pirgu Stage.
The current spatiotemporal distribution of bioherms is a result of interdependent factors that involve original drivers of reef development, such as relative sea level, climate during the time of deposition, and effects of post-depositional erosion. Oceanographic conditions were likely more favorable during times of cooler global climates, low sea level and glacial episodes. At the same time, the likelihood that bioherms are preserved from long time erosion is higher when deposited during low sea level in deeper parts of the basin.
A main factor controlling the timing of the reef and mound evolution was Baltica's shift toward palaeotropical latitudes during the Late Ordovician. The time equivalence between initial reef growth and the Guttenberg isotope carbon excursion (GICE) suggests that global climatic conditions were important. The long lasting stability, the resilience of individual mounds, and the increasing taxonomic diversity of the reefs/mounds suggest a significance of biological factors for the reef formation.

Keywords: carbonate platform, bioherm, mud mounds, Baltoscandia, Great Ordovician Biodiversity Event (GOBE)

1. Introduction

The most famous biogenic reefs of Baltoscandia are situated on the Baltic islands of Gotland, Sweden and Saaremaa, Estonia. These highly diverse reefs grew during the Silurian Period. Since at least the mid-twentieth century they have been known to form a barrier-like belt across the Baltic Basin (see reviews in e.g., Manten, 1971;

Flodén *et al.* 2001). Today, the Silurian reefs are considered to be an integral part of an extensive carbonate platform that evolved along the shelf areas at the south-western margin of the Baltic Shield and the East European Platform (e.g., Calner *et al.* 2004; Kaminskas *et al.* 2015). In contrast, the Ordovician reefs of the Baltoscandian region are less well known and are generally considered to have a more or less sporadic distribution in time and space (e.g., Webby, 1984, 2002; Cocks & Torsvik, 2005). Ordovician reef growth across Baltoscandia has often been linked to specific events and / or the general palaeolatidunal shift of Baltica towards the equator (e.g., Jaanusson, 1973; Webby, 1984, 2002; Cocks & Torsvik, 2005).

The Ordovician Baltoscandian reefs are part of the larger story of the evolution of Baltica, which gained its identity as a distinctive palaeocontinent during the Precambrian and merged with Laurentia during the Silurian Caledonian orogeny. The palaecontinent consisted of two main cratonic areas, the Baltoscandian or Fennoscandian and the East European craton (Cocks & Torsvik, 2005). Between the two cratons the large peri-cratonic Baltic Basin extended with thick sedimentary successions preserved across the southern and central part of the Baltic Sea and from the St. Petersburg area towards Poland (Poprawa *et al.* 1999; Fig. 1). Other important peri-cratonic basins developed on Baltica along todays' eastern margin of the palaeocontinent in the Timan-Pechora area and at the western slope of the Urals (Klimenko *et al.* 2011). During the Ordovician, Baltica's eastern margin faced north and was generally closer to the equator (Cocks & Torsvik, 2005). Extensive barrier-reef complexes developed during the late Katian along these palaeo-northern shelf edges (Antoshkina, 1996, 1998). In earlier compilations such reef complexes were not mentioned from the palaeo-SW epicratonic areas of Baltoscandia. But was this really the case? Ordovician barrier-reef-type complexes were described from seismic profiles from areas in the central Baltic Sea (Tuuling & Flodén, 2000). What kind of spatio-temporal pattern would emerge by mapping all the Ordovician reefs and mounds described in the literature?

Herein, we review the complete record of reefs and mounds described from the Ordovician successions of Baltoscandia (Fig. 2). With our review we are able to demonstrate that widespread reef and mound growth was part of the regional Ordovician story and that reefs and mounds shaped the formation of the carbonate platform in the Baltic Basin.

The references compiled for this review range from detailed published descriptions of complete depositional settings in surface exposures and drill cores to reports of reflection profiles, and to notes in unpublished field books of Estonian geologists. Additionally, we complemented some listings in the literature with new detailed sedimentological and stratigraphical investigations. The resulting spatio-temporal occurrence pattern is highly uneven not because of local differences in research effort – the entire region is well mapped by surface and subsurface data – but because of primary sedimentary differences and the present-day extent of Ordovician strata.
The results of this review also demonstrate that no direct inferences can be drawn from a simple diagram that would sum up the expansion and abundance of reefs in the Ordovician sediments of Baltoscandia. Today the original reef distribution is heavily biased and selectively degraded by large-scale erosion of the more proximal and coastal areas of the epicontinental basin. The recent northern limit of Palaeozoic sediments on the crystalline basement of the Fennoscandian shield is represented by a more than 1200 km long Cenozoic erosional escarpment, the Baltic Klint (e.g., Tuuling & Flodén, 2010). Only few locally restricted occurrences preserve and expose Ordovician deposits on the Swedish mainland, in the Bothnian Sea, and at the Åland Islands in the central Baltic Sea. The mounds and reefs are often concentrated in the regions close to the Baltic Klint and in isolated areas on the Fennoscandian shield N and W of the Baltic Klint. These areas were more proximally positioned during the Ordovician than most of the regions south of it.
Herein, the actual spatial and stratigraphic distribution of Baltoscandian reefs is reconstructed as a result of an original pattern that was subsequently eroded in a non-random way. Our reconstructions may encourage palaeobiologists to test hypotheses about the controlling factors of the reef formation in Baltica, such as climate, tectonics, oceanography and ecosystem stability.

2. Methods

Most of the data included herein were compiled from peer-reviewed journal articles, published reports, Ph.D. theses, and archived field notes (Supplementary Material, Table 1). The resulting data compilation represents the complete publicly available knowledge about reefs in Ordovician strata of the Baltoscandian region.

New information and data where collected from the Võhma drill core section (58.612260°N, 58.612260°E), Viljandi County, central Estonia (Fig. 2). The core section is preserved in 90 core boxes at Tallinn Technical University Särghaua field station. For this review the Võhma drill core section was logged based on core, polished slabs where produced at Tallinn Technical University, and thin sections generated at the GeoCenter of Northern Bavaria in Erlangen (Germany). Detailed sedimentological and palaeontological descriptions will be published elsewhere.
We present a new carbon isotope dataset for the Võhma drill core. A number of 128 samples were drilled and analyzed to develop a detailed middle Katian through early Hirnantian $\delta_{13}C_{carb}$ curve (Nabala through Porkuni Stages) across the mound bearing interval (Supplementary Material, Table 2). The carbonate powders were reacted with 100% phosphoric acid at 70°C using a Gasbench II connected to a ThermoFinnigan Five Plus mass spectrometer. The analyses were carried out at the Laboratory of M. Joachimski at the Geocenter of Northern Bavaria in Erlangen (Germany), and all values are reported in per mil relative to V-PDB (Vienna Pee Dee Belemnite) by assigning a $\delta_{13}C$ value of +1.95‰. Accuracy and precision was controlled by replicate measurements of laboratory standards and was better than ±0.2‰ for the carbon isotope data (0.13 ‰ in an average).
$\delta_{13}C$ chemostratigraphy is generally accepted as a powerful tool for the correlation of Baltoscandian Middle and Late Ordovician carbonate successions (e.g. Ainsaar *et al.* 2004, 2010; Kaljo *et al.* 2007; Bergström *et al.* 2015). Based on lithostratigraphy and the $\delta_{13}C$ data we can confidently correlate the Võhma drill core section with other sections in the eastern Baltic area, and across Balticoscandia.
The diversity estimates are based on queries from the Palaeobiology Database (https://paleobiodb.org/) from 03/2015 (for occurrences of Boda Limestone and Kullsberg Limestone Formations), and from the Estonian geocollections database SARV (http://geokogud.info/) from 04/2015 (for occurrences in Estonia). The records of the Palaeobiology Database represent the complete set of published palaeontological literature about the target interval and region, and were in large parts entered by one of the authors of this review (BK). The SARV database comprises the complete set of taxonomically determined specimens in the geocollections of Estonia (see http://geokogud.info/).
The diversity estimates were calculated by rarefaction with the R-package Vegan (Oksanen *et al.* 2013). Additionally, detection probabilities of genera were calculated

based on occupancy modeling (MacKenzie *et al.* 2003, 2004), a Capture-mark-recapture method (CMR) with the R-package unmarked 0.10-5 (Fiske & Chandler, 2011). For a general introduction to CMR approaches in palaeontology see Liow & Nichols (2010). Here we compiled the Estonian occurrences of genera downloaded from the SARV database within selected time slices (Keila, Oandu, Rakvere, Nabala, stages, and Moe Formation). We grouped the collections in 'sites' (groups of localities which are nearby, Vasalemma settlement, Rakvere city, Ristna, etc). The individual collections, such as, Vasalemma Nordkalk quarry, Vasalemma rallye quarry, Vaselemma drill core 1044, etc., then represented 'replicates' of one site. The database was not sufficient in order to calculate reliable occupancy estimates, the resulting confidence intervals were too large, but the detection estimates provide important information (Table 1). We assume no significant differences in sampling effort between the samples of the different time slices and as a consequence interpret the detection probability as a proxy for the relative taxon abundance within the sites. High detection probabilities are interpreted as indicating higher average abundances of taxa in the respective time slice.
The stratigraphic correlation is based on published reports on bio-, litho- and chemostratigraphy of the target intervals (e.g. Ainsaar et al. 2010; Bergström et al. 2010*a*; Bauert et al. 2014; Ebbestad et al. 2015). Additionally, stratigraphical gaps were identified in individual sections. In most of the sections non-deposition and erosion prevailed and only parts of the transgressive and highstands intervals of the 3rd and 4th order depositional sequences are recorded (see e.g., Dronov, 2011; Nielsen, 2011). In our correlation schemes the identifiable gaps within the individual sections have been incorporated as empty intervals in the graphical depiction. The absolute lengths of the gaps, however, are unknown. Hence, the depictions give only a rough estimate of the pattern of deposition and non-deposition. This method was inspired by Ernst *et al.*'s (1996) 'Lückenstratigraphie' of the Late Cretaceous sediments across Europe (see also Wilmsen *et al.* 2012).

3. An account of Baltoscandian reef and mud mound occurrences

3.a. Pre-Katian reefs and mud mounds

3.a.1. Lower Ordovician Hecker-type mud mounds of the St. Petersburg region

Almost all bioherms known from Baltoscandia and its vicinity are Late Ordovician in age (Fig. 3). There is only one exception, the mud mounds in the glauconitic limestone of the Billingen–Volkhov stages (late Floian–Dapingian) in the St. Petersburg region (Federov, 2003). A number of c. 15 individual mounds were listed by Tolmacheva et. a. (2003). The mounds form flat structures with diameters of up to more than hundred meters and maximum thicknesses of no more than 5 m. These specific morphologies are considered to be a caused by in situ concentrations of siliceous sponges, their microbial decay, and formation of automicrite, and are termed Hecker-type mounds (Fedorov, 2003, and references therein). Currently no evidence exists that these types of mounds were more widespread across the Baltic Basin or adjacent epicratonic areas.

3.a.2. An isolated 'atoll-reef' south of Stockholm, Sweden

Flodén *et al.* (2001) mentioned an 'atoll-reef' along the syndepositional rim of the Tvären meteorite crater south of Stockholm, Sweden. The existence of this reef is highly questionable. Flodén *et al.* (2001) refer to a paper by Lindström *et al.* (1994), where biohermal deposits are not mentioned but instead a faunal list of the upper third of the crater infill is given with a 'diversified biota include abundant pelmatozoan echinoderms, bryozoans, major brachiopods, trilobites, and ostracodes, as well as calcareous algae, collectively suggesting that living conditions on the upper part of the rim wall may have been reef-like' (Lindström *et al.* 1994, p. 101). The infill is time equivalent to the Sandbian Dalby Limestone (Kukruse Stage), and evidence for biohermal sediments do not exist. Instead a detailed analysis of the infill by Frisk & Harper (2013) suggests that faunal elements existed that lived on a hard substrate at the crater ring during the time of deposition of the crater infill. Details about the specific crater rim are not known.

3.b. Late Sandbian / Early Katian reefs and mud mounds

The late Keila to early Oandu Regional Stage interval records the first widespread occurrences of reefs and mounds in Baltoscandia (time-equivalent to the Chatfieldian Regional Stage in North America, and Sa 2/ Ka1 Stage Slice of Bergström et al. 2009). Framework reefs of this time interval are exposed in several places in Norway, and Estonia, and mud mounds are exposed in the Siljan area, central Sweden (Figs. 2, 3). Subsurface occurrences of mud mounds were reported from Östergötland, Sweden and the Bothnian Sea.

3.b.1. Reefs of the Steinvika and Mjøsa Limestones, Norway

Late Sandbian / early Katian reefs occur in two distinct areas in the Ordovician of the Oslo Region; in the Steinvika Limestone of the Skien-Langesund district, and in the Mjøsa Limestone of the Toten and Nes-Hamar districts (Fig. 2). In both areas the reefs developed in a nearly contemporaneous time interval during the earliest Katian (Harland, 1981; Owen, 1990; Bergström *et al.* 2010*b*, 2011*b*, see below).

Three types of patch reefs and an additional larger reef complex can be distinguished. (1) In the Furnesfjorden Member of the Mjøsa Limestone up to 15 m thick reefs occur, which are formed by loose clusters of large nodular colonies of the chaetetid sponge *Solenopora* with occasional occurrences of the tabulate *Eofletcheria irregularis* (Opalinski & Harland, 1981). (2) In the Eina and Bergevika Member of the Mjøsa Limestone patch reefs with thicknesses of c. 5 m and diameters of up to 20 m occur, which in their lower parts are built by *E. irregularis*, clusters of *Solenopora*, and the green algae *Vermiporella*. In the upper parts the reefs are mainly built by domal labechiid stromatoporoids (*Labechia*, *Pachystylostroma*, *Radiostroma*, see Webby, 1979) and massive tabulates (*Lyopora*) (Opalinski & Harland, 1981; Harland, 1981). (3) In the Bunes Member of the Steinvika Limestone up to 35 m wide patch reefs occur, which are characterised by abundant echinoderm holdfasts. In the lower parts these reefs were formed mainly by echinoderm holdfasts and microbial limestone, in the middle part *E. irregularis* is more common and in the upper parts domal stromatoporoids, and large massive closely packed tabulates (*Tryplasma*, *Lyopora*) dominate. (4) A more than 50 m wide massive reef complex occurs in the Bergevika Member of the Mjøsa Limestone. The reef is in central and upper parts built by massive domal labechiid stromatoporoids. In more marginal areas algae such as *Dimorphosiphon*, *Vermiporella*, the problematic *Girvanella*, and tabulates, such as *Eofletcheria* and *Catenipora* locally are common components.

All four reef types formed on local shoals and banks of pelmatozoan grainstone, and this grainstone partly also occurs in the direct flanks of the reef bodies. Another aspect the four reef types have in common is the relatively high percentage of frame builders. The percentage of matrix, such as microbialites, wackestone and biodetritic limestone is in average c. 40% (P. R. Opalinski, unpubl. Ph.D. thesis, University of

Liverpool, 1977, fig.5.16; see Supplementary Material, Table 1). The reefs represent cluster-frame reefs in the terminology of Riding (2002). Harland (1981) interpreted the depositional setting of the patch reefs as ‘within inshore shelf’ and the larger massive reef complex in the Bergevika Member as deposited at the outer edge of an inshore shelf. The reefs probably were part of the local carbonate platform in the present SW of the hypothetical Telemark Land.

3.b.2. Reefs of the Vasalemma Formation, Estonia

The Vasalemma Formation is distributed and exposed exclusively in an area SW of Tallinn in the vicinity of the settlements Vasalemma and Saku. There, in a narrow 30 km WSW-ENE striking and 5 km N-S stretching belt, the pelmatozoan grainstone facies of the Vasalemma Formation was deposited (Fig. 2). The belt is delimited towards the north by the northern boundary of the outcrop area and towards the south by a depositional gap of time equivalent deposits. Within the massive, up to 15 m thick Vasalemma Formation locally patch reefs were formed with diameters of up to 50 m and thicknesses of up to 15 m (see Kröger *et al.* 2014a for review). The reefs are generally composed of a bryozoan, and echinoderm framestone to bindstone, with *Hemiscosmites* holdfasts and encrusting bryozoans as main metazoan constructors, locally, receptaculitids were important additional bafflers (Kröger *et al.* 2014a, Fig. 4A). At the top of the reefs large colonies of *Eofletcheria orvikui* are common. The reefs are relatively matrix rich with matrix contents of 50-70%. The matrix of the reefs is generally composed of a mottled microbialite and microbially controlled early lithification played a major role for the formation of the Vasalemma reefs (Kröger *et al.* 2014a). New palaeogeographical reconstructions assumed that the reefs formed in the central parts of the shallow Estonian shelf which was highly differentiated into local shallow basins and shoals, and which probably extended further to the NW in areas in where Late Ordovician deposits are eroded today (Kröger *et al.* 2014a).

3.b.3. Mud mounds of the Kullsberg Limestone Formation, Lake Siljan area, central Sweden

A number of c. 35 individual Late Ordovician mud mound structures (Jaanusson, 1982) are preserved in the sedimentary fill of the ring-like graben system around the central uplift of the late Devonian Siljan impact crater in central Sweden (Juhlin & Pedersen, 1987; Jourdan *et al.* 2012); Fig. 2. The outer diameter of this ring graben is

c. 52 km wide and represents the only Early Palaeozoic sediments preserved in an extensive area in central Sweden where only crystalline basement is exposed. The mounds formed during two distinctive periods during the earliest Katian (Kullsberg Limestone mounds, short: Kullsberg mounds) and latest Katian–earliest Hirnantian (Boda Limestone mounds, short: Boda mounds).

The two generations of mounds have several features in common; both are composed of massive stromatactis limestone (Ross *et al.* 1975; Jaanusson, 1978; Bathurst, 1982; Riding, 2002; Tobin *et al.* 2005; Kröger *et al.* in press), and a flank region composed of coarse-grained pelmatozoan wacke-, pack-, and grainstone (Paul & Bockelie, 1983; Calner *et al.* 2010*b*; Kröger at al., in press). The Kullsberg mounds are smaller in dimensions (c. 40-50m thick and up to 350m wide; Jaanusson, 1982) and are less abundant (11 mounds are listed in Jaanusson, 1982, and Ebbestad & Högström, 2007), and the facies and fauna of the Kullsberg mounds is little studied (Jaanusson, 1982; Calner *et al.* 2010*b*). The occurrence of dasycladacean green algae, Solenopora, and fragments of *Girvanella*, as well as the presence of cross-bedded pelmatozoan grainstone lithologies, and disarticulated ostracods indicate relatively high water current energies and depths of < 50 m for the deposition of the Kullsberg mounds (Tobin et al. 2005).

3.b.4. Poorly known mud mounds in the Bothnian Sea, E of Öland, and in Östergötland, Sweden

Occurrences of mud mound complexes, probably of the same age like those in the Kullsberg Limestone (earliest Katian) were reported from the southern Bothnian Sea (Winterhalter, 1972; Söderberg & Hagenfeldt, 1995) and from the subsurface of Östergötland (Jaanusson, 1979) (Fig. 2). The short reports are based on seismic profiles and no details about the sizes, the specific ages and the composition of the structures are given. Several isolated mud mound structures were also identified in a subsurface area offshore E of Öland (Flodén, 1980). The structural position of these mounds suggests an earliest Katian age, probably time equivalent to the Kullsberg Limestone in central Sweden.

3.c. Middle Katian mud mounds

Few reports of middle Katian Baltoscandian mud mounds, and no reports of middle Katian framework reef exist, but indirect evidence suggests that algal-rich mud mounds of a Nabala–Rakvere Stage age (time quivalent to Ka2, and Ka3 Stage Slices of Bergström et al. 2009) are or were widespread in the Central Baltic and Bothnian Sea.

In the subsurface of Gotland a horizon with mud mounds with a thickness of tens of meters occurs in drill cores, which is called the Liste mound horizon (Liste Member of the Östersjö Formation; Bergström et al. 2004 and references therein). Chitinozoans and conodonts indicate the *Fungochitina spinifera* and *Amorphognathus superbu*s biozones for the Liste mounds (Bergström *et al.* 2004; Shived et al. 2004). This is time equivalent to the upper part of the Slandrom Limestone, Nabala Stage (Bergström *et al.* 2004). The Liste mounds are stromatolitic mud mounds, partly rich in brypsidalean green algae similar in lithology to the mud mounds of the Pirgu Regional Stage in the same region (Shived et al. 2004; see below).

Additionally, in the central Baltic area seismic profiles indicate the presence of few reefs or mounds in a horizon below the prominent reflector $O_{4–5}$ (= below Vormsi Stage, Tuuling & Flodén, 2000) and it was speculated that these are time equivalent to the Kullsberg mounds (Tuuling & Flodén, 2010). However, the exact stratigraphic age of these structures is not known and the possibility exists that some of them are of Rakvere–Nabala age.

Limestone boulders with brypsidalean green algae (e.g. *Vermiporella*, *Palaeoporella*) framestone to bafflestone lithologies are known from within Pleistocene sediments across the southern Balti, and central Sweden (Wiman, 1908; Hucke, 1967; Kozlowski & Kazmierczak, 1968). The algal limestone boulders belong to the so-called Baltic Limestone, *Ostseekalk* of the older literature, and the Östersjö and File formations of the Central Baltic and Bothnian Sea (Bergström et al. 2004). Biostratigraphic data indicate that a significant amount of these limestones is time equivalent to Rakvere–Nabala Regional Stage (Wiman, 1908; Hucke, 1967; Bergström et al. 2004, and references therein). The only in situ occurrences of similar algal framestone – bafflestone lithologies are known from Pirgu Stage mud mounds across the Baltoscandian region (see below). It can be concluded that similar, but older, Rakveran–Nabalan age, algal-rich mud mounds occur and occurred in the central Baltic–Bothnian Sea area.

3.d. Late Katian reefs and mud mounds

Late Katian, Pirgu Stage (time equivalent to Ka4 of Bergström et al. 2009) reefs and mud mounds are most widespread across Baltoscandia and a variety of reports exist from outcrops, drill cores, and seismic data that provide a detailed picture of that time interval.

3.d.1. Mud mounds of the Boda Limestone Formation, lake Siljan area, Sweden

More than 20 individual mud mound structures exist in the ring-like graben system of Siljan impact crater that belong to the Boda Limestone Formation, late Katian–early Hirnantian (Jaanusson, 1982, see also paragraph 3.b.3, and Fig. 2). The mounds are composed of massive stromatactis limestone (Ross *et al.* 1975; Jaanusson, 1978; Bathurst, 1982; Riding, 2002; Tobin *et al.* 2005; Kröger *et al.* in press), and a flank region composed of coarse-grained pelmatozoan wacke-,pack-, and grainstone (Paul & Bockelie, 1983; Kröger at al., in press). The mounds in the Boda Limestone reach dimensions of up to 1000 m in diameter with a thickness of more than 100 m. In a recent review, Kröger *et al.* (in press) noted that the stromatactis bearing core limestone of the Boda mounds is generally very rich in sponge spicules and assumed that sponge decay and microbial activity probably was a key factor in mound formation. Beneath typical stromatactis limestone (Fig. 4D), the Boda mounds contain a substantial amount of massive limestone with a mosaic-like pattern of diffuse cryptocrystalline patches, which are unlike stromatactis filled with compact masses of bladed-blocky spar. Additionally, the Boda mounds have a significant portion of *Palaeoporella* framestone to bafflestone in their core regions (Stolley 1898; Thorslund, 1936; Jux, 1966, Kröger *et al.* in press). The algal limestone is interpreted as evidence for an active, constructing role of brypsidalean green algae in the mound formation and as main (originally aragonite) carbonate producers of the mounds. The formation of the Boda mounds is assumed to be a result of a combined mechanism of early aragonite recrystallization and organomineralisation with green algae and sponges as main mound constructors.

The general faunal composition of the mounds, and their flanks, and a low energy depositional environment are interpreted as evidence for the position of the mounds low in the photic zone at water depths of 50-100 m (see Kröger & Ebbestad, 2014, and references therein).

3.d.2. Reef and mud mound complexes of the Central Baltic area

From Gotland in the SW to the Island Hiiumaa in Estonia in the NE stretches a nearly 300 km long, and up to 40 km wide belt across the Central Baltic in which more Ordovician reefs and mounds existed than anywhere else on Baltoscandia (Fig. 2). This extensive belt is known from seismic reflection profiles (Flodén, 1980; Tuuling & Flodén, 2000, 2010, and ref. therein). Based on seismic reflectors and biostratigraphical data from drill cores the age of these reefs and mounds can be constrained to Pirgu – Hirnantian Stage (Bergström et al. 2004; Tuuling & Flodén, 2000, 2010). The northward extension boundary of the belt roughly coincides with the submarine exposure and northward extension boundary of the Pirgu–Hirnantian beds and with the Baltic Klint.

Two main areas with reef / mound concentrations can be distinguished, a larger western area with a center closely NE offshore Gotland, and a minor SW offshore Hiiumaa. In the Gotland area, seismic reflection pattern reveals a general zonation of the belt with (1) a 1-4 km wide 'main zone' or 'barrier zone' with of up to 2 km in diameter closely spaced buildups in the north, followed by (2) an up to 12 km wide zone with clusters of solitary buildups, each 500-800 m in diameter, and with distances of several hundred meters, and in the south (3) a more than 20 km wide zone with generally smaller solitary structures (Tuuling & Flodén, 2000). In the area SE of Hiiumaa the buildups have generally smaller sizes (100-200 m in diameter) and are distributed in more widely dispersed clusters (Tuuling & Flodén, 2000).

In the main zone, the buildups are locally tightly spaced and form 'a single monolithic body', in places where they are spatially more separated. The shapes of individual structures are flat and symmetrically lenticular with a thickness of generally considerably less than 100 m (Tuuling & Flodén, 2000; see also Sivhed *et al.* 2004). Basinward from the main zone the buildups are smaller in lateral dimensions but similar or greater in thickness (40-50 m) resulting dome-cone shaped structures (Tuuling & Flodén, 2000). Hypotheses about details of the bioherm architecture, its constructors and differences among specific regions remain largely speculative because only few drill core studies are available (Bergström *et al.* 2004; Sivhed *et al.* 2004; Eriksson & Hints, 2009).

Sivhed *et al.* (2004) demonstrated that several bioherms in the subsurface of Gotland are composed of a regular pattern of a sub-mound and flank facies that consists mainly of pelmatozoan pack-wackestone, and massive *Palaeoporella* and stromatactis-rich core regions. Sivhed *et al.* (2004) also mentioned 'stromatolitic limestone', but all his figured samples only show typical stromatactis cavities, which were mistaken as stromatolites. Based on a comparison of the figures of Sivhed *et al.* (2004), the Gotland mounds were very similar to the mud mounds of the Boda Limestone and of central Estonia (see paragraph 3.c.1) and probably were formed in a very similar manner.

3.d.3. Reefs and mud mounds of the Pirgu Stage of Estonia

Reefs and mud mounds of the Pirgu Stage are preserved at several places along the Estonian shelf. Generally more shallow depositional settings can be distinguished with small patch reefs within the aphanitic limestone of the Moe Formation and deeper settings with massive mud mounds within the argillaceous limestone and marls of the Jonstorp Formation. The patch reefs are exposed at Vormsi Island (Hoitberg: 59.004444°N, 23.182778°E) and slightly eastward in NW Estonia (Ruunavere: 59.090533°N, 24.459025°E ; and Niibi: 59.040833°N, 23.656389°E) and only little information is available from Klaamann (1966), Kaljo (1957), and unpublished field notes of L. Põlma, and H. Nestor (available at: the database of the Geocollections of Estonia, http://geokogud.info/). The Hoitberg reef is more than 3 m thick and 45-65 m in diameter, the Ruunavere and Niibi reefs are less than 1 m thick and only a few meters in diameter. The reported common occurrence of tabulates such as *Catenipora*, *Cryptolichenaria*, *Eocatenipora*, *Sarcinula*, and heliolitids in the reefs indicate a significant role of corals for the reef construction. Additionally, stromatoporoids such as *Clathrodictyon*, and *Plumatilinia* and green algae such as *Palaeoporella* and *Vermiporella* played a major role for the reef formation.

Large mud mounds formed in deeper depositional environments during the Pirgu Stage (Perens, 1995; Hints *et al.* 2005). The only well-documented mound is known from the Võhma drill core of central Estonia (58.612260°N, 25.559460°E) (Alikhova, 1953; Oraspõld, 1982; Raukas & Teedumäe, 1997, Figs. 2, 5). The recorded thickness of the mound is c. 53 m, its base is within the Jonstorp Formation and the top within the Adila Formation. The mound facies is generally very similar to the mounds of the Boda Limestone Formation in central Sweden, and to the mounds in subsurface Gotland (see Section 3.d.2 above); it consists of massive stromatactis and *Palaeoporella* limestone (Fig. 4B). An interesting detail of the mound's faunal composition is the increased abundance of isolated halysitid colonies, such as

Catenularia in the uppermost parts of the mound. This is similar to the Boda limestone mounds and probably indicates a relative shallowing at the final mound growth during the terminal Pirgu Stage (see Kröger *et al.* in press).
A less than 2 m thick section of stromatactis limestone in the Võhma drill core within the rising limb of the Hirnantian Isotopic Carbon Excursion (HICE) (Fig. 5), represents either a distinct younger smaller mound or a wedge of a continuous mound forming process. The mound growth also continued during the Hirnantian with a reduced intensity in the Siljan district, Sweden (Kröger *et al.* in press).

3.d.4. Reefs of the Pirgu Stage of SE Latvia and Lithuania

The occurrence of small patch reefs is also reported from drill cores in the Moe and Adila formations, Pirgu Stage in Ludza-15 (56.545959°N, 27.713909°E) and Malta-105 (56.335816°N, 27.172612°E) drill cores, SE Latvia (Ulst, 1972; Ulst *et al.* 1982; Fig. 2). A detailed description of the reefs is not available, but tabulate corals are listed as a frame-building component (Ulst *et al.* 1982, p. 97). Algal-coral stromatoporoid bioherms were listed from beds of the Pirgu and Porkuni Stage in the Pamituvys-98 core in Lithuania (Laškovas, 2000).

3.e. Hirnantian reefs and mud mounds

During the early Hirnantian (equivalent to Hi1 Stage Slice of Bergström et al. 2009) the large mud mounds of the Boda Limestone Formation, central Sweden, and the mud mound of the Võhma drill core, Estonia continued to growth (see Section 3.d. above). Additionally, a number of framework reefs are reported from shallow depositional environments of Estonia and Norway.

3.e.1. Hirnantian bioherms of the Oslo region, Norway

Latest Ordovician bioherms of the Oslo region are listed in the literature but are generally very poorly known (e.g., Nakrem & Rasmussen, 2013, p. 64). Bioherms are described in an unpublished thesis from latest Ordovician sandy sediments from southern end of the Oslo region in the Skien-Langesund area (Braithwaite *et al.* 1995; Fig. 2). Details of the stratigraphy and sedimentology of these bioherms are not known. The ‘reefs’ at Ullerntangen, Ringerike area, that were originally described by Kiaer (1897), and named ‘carbonate bank’ in Hanken & Owen (1982), are interpreted as debris flow sediments by Braithwaite *et al.* (1995). The debris flow ‘carbonate bank’ should not be confused with directly underlying ‘small argillaceous mounds’ which also occur in the near Store Svarteøya island southeast of Ullerntangen (Hanken & Owen, 1982, pers comm. B. Gudveig Baarli, 2015). The mounds are embedded in a pelmatozoan grainstone, attain a thickness of less than 3 m and contain abundant stromatoporoids and tabulate corals (Hanken & Owen, 1982). The stratigraphy of the pelmatozoan wackestone and the embedded mounds is poorly resolved, but regarded as equivalent to the Hirnantian Langøyene Sandstone elsewhere (Braithwaite *et al.* 1995).

3.e.2. Hirnantian reefs of Estonia

Hirnantian shallow water patch reefs developed in many places of northern Estonia within the Ärina Formation (Oraspõld, 1975; Perens, 1995; Hints *et al.* 2000, Fig. 2). Details about the composition of these reefs are not known, but general faunal descriptions indicate that stromatoporoids auch as *Clatrodictyon*, *Ecclimadictyon*, and *Pachylostoma* were the main metazoan constructors (Nestor, 1964, 1999). Additionally, tabulates, such as *Eocatenipora* and *Paleofavosites*, are important metazoan components (Klaamann, 1966). Tetradiid corals such as *Rhabdotetradium* played an important role as baffler in the younger reef generation of the Tõrevere Member (compare Oraspõld, 1975; Hints *et al.* 2000). Our own investigations in the Porkuni quarry (59.187346°N, 26.187433°E) indicate that small patch reefs, which developed during the older Vohilaid – Siuge Member of the Ärina Formation have a core facies with a content of more than 60% of a clotted microbial limestone. Additionally, encrusting stromatoporoids, encrusting bryozoans and baffling dasycladaceans played a major role for the reef formation (Fig. 4C).

4. Stratigraphy of the reef/mound horizons and reef/mound community evolution

Mud mounds and framework reefs became widespread in the Baltoscandian area during the Late Ordovician (Fig. 6). The oldest Baltoscandian bioherms are small, regionally restricted mud mounds within Early Ordovician limestone. During the earliest Katian reefs and mounds spread across Baltoscandia and a high diversity of frame builders ranging from bryozoans, echinoderms, and receptaculites to stromatoporoids and tabulate corals, are present in strata of the Keila Stage. Middle and late Katian frame reefs are characterized by a more distinct dominance of stromatoporoids and tabulates, and often contain green algae as significant components. Green algae are an important component of the large late Katian stromatactis mud mounds. Diverse frame reefs and stromatactis mud mounds are present in early Hirnantian strata. These reefs and mounds do not reach into late Hirnantian strata.

4.a. Pre Katian reefs/mounds

The only pre-Katian reef/mound structures known from Baltoscandia are the flat sponge-rich microbial mud mounds of the Billingen–Volkhov stages (late Foian – Dapingian) in the St. Petersburg region. During the Floian – Dapingian this region was part of a proximal area of the interior of the Baltic Basin, a flat ramp like sedimentary system with a deposition of temperate siliciclastic-glauconitic limestones in a storm-dominated environment (Dronov, 2005). The formation of mud mounds seemed to be restricted this specific area of Baltoscandia.

4.b. Keila–Oandu Stage reefs/mounds

The late Sandbian / early Katian was a time interval with major changes in the sedimentary regime throughout Baltica. Ainsaar *et al.* (2004) named the interval 'Middle Caradoc Facies and Faunal Turnover' and emphasized on the remarkable and probably interconnected changes in facies, sea level, climate and biota. The formation of reefs and mud mounds and their termination is a major aspect of this event.

The baseline and key horizon for the correlation of the early Katian beds is the late Sandbian Kinnekulle K-bentonite bed (Sell *et al.* 2013; Bauert *et al.* 2014). The sediments above the Kinnekulle K-bentonite record a conspicuous δ_{13}C peak, the Guttenberg Isotope Carbon Excursion (GICE), which can be observed in North America and elsewhere in the world (Bergström *et al.* 2010*a, c;* Sell *et al.* 2015).

In Baltoscandia, the GICE interval and its directly overlying beds are characterized by pronounced depositional gaps. Two major hiati, an earlier during the peak GICE interval and a later in the final GICE interval can be traced over the entire Baltoscandian basin. Reefs and mud mounds are exclusively concentrated across Baltoscandia in beds representing the narrow time interval of the rising limb and peak interval of the GICE below the major sedimentary gaps (Fig. 7).

Framework reefs of this time interval are present in the Oslo Region at the margin of the Baltic Basin, and in northern Estonia in more interior parts of the basin (Fig. 6). In both areas root-like echinoderm holdfast locally played a major role as sediment binders and bafflers. Otherwise, the reefs of two regions are very different: The reefs of the Oslo Region are relatively matrix poor with a content of 40% in average, in contrast the Estonian reefs have a matrix content of 50-70% (see Section 3.d. above). The Estonian reefs are mainly composed of sheet forming bryozoans, *Hemicosmites*-holdfasts, and receptaculites and microbial limestones are an important component. The Norwegian reefs, in contrast, are formed by *Solenopora*, stromatoporoids, and tabulate corals and in several places contain green algae as an important component. In the Estonian reefs, tabulate corals are restricted toward the last phase of reef growth and stromatoporoids and green algae are totally absent. Echinoderm-rich, and receptaculite-rich reefs are stratigraphically restricted in Baltoscandia toward late Sandbian / early Katian strata. Stromatoporoids and tabulate corals became the dominant reef frame builders later during the Ordovician period. Sedimentological characteristics, such as the presence of pelmatozoan-grainstones, cross bedding indicate shallow neritic depositional envrironments for the late Sandbian / early Katian frame reefs. The stromatactis mud mounds of the time equivalent Kullsberg Limestone probably were deposited in slightly deeper, but also shallow neritic depositional environments (Tobin et al. 2005). However, lithology and biotic content of the Kullsberg mounds are little studied and a detailed discussion impossible with the current data.

4.b. Rakvere–Nabala Stage reefs/mounds

Little is known about the stratigraphical level and the palaeogeographical extend middle Katian reefs/mounds. The only unequivocal place of mud mounds of Rakvere–Nabala age is the subsurface of Gotland, where drill cores indicate a mound lithology that is identical to the younger mounds of e.g. the Boda Limestone. These mounds are mainly composed of a sponge rich stromatactis limestone and by a green algal (e.g. *Palaeoporella*) framestone and bafflestone and are interpreted to be a result of a spectrum of essentially microbially mediated diagenetic accretionary mechanisms (Kröger et al, in press). Seismic profiles led to suggest that more middle Katian mounds of the same type are present below younger, more massive mound structures in the Central Baltic (Tuuling & Flodén, 2000; Tuuling & Flodén, 2010). The widespread occurrence of *Palaeoporella* limestone boulders with Rakvere–Nabala age microfossils within Pleistocene erratics can be interpreted as additional evidence that middle Katian green algal rich mud mounds were not an isolated phenomenon of subsurface Gotland (see Section 3.d. above).

4.c. Pirgu Stage

During the entire Pirgu Stage interval reefs and mounds flourished within the Baltic Basin (Fig. 6). Most prominent and best investigated are the mounds of the Boda Limestone Formation in the Siljan district of central Sweden (Ebbestad *et al.* 2015; Kröger *et al.* in press, and refs therein). In the Siljan district the mound growth started immediately after the deposition of the Fjäcka shale within the lower Jonstorp Formation, early in the Pirgu Stage, and lasted with minor disturbances until the early Hirnantian (Kröger *et al.* in press, and refs therein).

The reefs and mounds in subsurface Gotland and in the central Baltic area by high probability had similarly long growth intervals. Chitinozoans indicate upper *Tanuchitina bergstroemi – Conochitina rugata* zones of the Pirgu Stage for these structures (Bergström *et al.* 2004). The mound and reef complexes offshore of Gotland and in the central Baltic area with a few exceptions occur between seismic reflectors O_{4-5} and Or_2, S_1 respectively and are thus younger than Vormsi Stage and generally older than Porkuni Stage (Tuuling & Flodén, 2000, 2010). The thick mound exposed in the Võhma drill core ranges from low in the Jonstorp Formation into beds representing the lower part of the HICE.

The exposed mud mounds of central Sweden, of subsurface Gotland, and of central Estonia are sedimentologically very similar, they consist of sponge-spicule rich stromatactis limestone cores and additionally contain significant parts composed of *Palaeoporella* framestone and bafflestone. Microbially mediated sponge biomass degradation and *Palaeoporella* skeleton disintegration and associated diagenetic processes are considered to be the main processes behind the mud mound formation (Kröger et al. in press). The mud mounds invariably occur in a narrow belt of the Baltic Basin, which is transitional between reddish argillaceous sediments and fine grained platform carbonates. The maximum depositional depth of the Boda Limestone mounds was low with the photic zone with depths of significantly more than 50 m (Kröger et al. in press).

The large mud mounds and mound complexes of the deeper depositional environments must be contrasted with the smaller mounds or framework reefs of the shallower environments, which are exposed in few places in north-western Estonia and described from drill cores in south-eastern Latvia and Lithuania. These structures generally have shorter stratigraphical ranges within the Pirgu Stage. Sedimentological details about these structures are not known, but frame builders, such as tabulate corals and stromatolites played an important role and green algae, such as *Palaeoporella* are ubiquitous.

4.c. Hirnantian

The Baltic Hirnantian succession is characterized by major sedimentary hiati (Kaljo *et al.* 2008; Bergström *et al.* 2012; Ebbestad *et al.* 2015). The growth of the mud mounds at the Siljan area, Sweden and at Võhma, central Estonia was terminated within the rising limb of the HICE, below the first major Hirnantian hiatus. The shallow water reefs reported from Ärina Formation of northern Estonia (Oraspõld, 1975; Hints *et al.* 2000) range throughout the recorded HICE interval.
The intercontinental correlation of the Hirnantian horizons of Baltoscandia with other sections in the world is problematic. This is mainly because of a lack of overlap of stratigraphically relevant chitinozoans, conodonts or graptolites. The chitinozoan index species *Spinachitina taugourdeaui*, which occurs in the lower two members of the Ärina Formation, indicates early Hirnantian age for most of the Porkuni Stage reefs of northern Estonia (Hints *et al.* 2000).
The large stromatactis mud mounds of central Sweden and central Estonia continued to grow, although in reduced intensities during the early Hirnantian. Notably the uppermost parts of these mud mounds occasionally contain heliotid tabulate corals as additional biotic component, which probably indicates changes in environmental conditions or decreasing depositional depths.
Small mud mounds or framework reefs are widespread in lower Hirnantian strata in northern Estonia and occur in the Oslo region (Fig. 6). Sedimentological details about the reefs are not known, but frame-builders, such as tabulate corals, stromatoporoids, and bryozoan are present and microbially mediated mineralization processes played a major role in the reef formation (see Section 3.e. above).

5. Interpretation

5. a. Early Katian change in mode of carbonate production in the Baltic Basin

Reefs and mounds were abundant in parts of the Baltic Basin from the latest Sandbian / earliest Katian boundary interval onwards (Fig. 6). During the latest Pirgu Regional Stage (latest Katian) a situation was established in the Baltic Basin, that was quite similar to that of the Silurian period, with barrier reef or mound complexes on a gently dipping carbonate platform (see chapter 3.d.2.; Tuuling & Flodén, 2000, 2010). The widespread appearance of bioherms marks a critical time-point in the evolution of the Baltic Basin. The earliest Katian regional Keila/Oandu stage boundary, which in northern Estonia is developed as a prominent facies change and hiatus, was recognized since a long time as a distinctive turning point in the evolution of the Baltic Basin. Estonian geologists drew at this hiatus the boundary between two evolutionary epochs or stages of the basin with an assumed major change in the tectonic regime (Männil, 1966; Hints *et al.* 1989, and references therein). Before the Oandu Stage, accordingly, the lateral facies differences across the basin were extremely low (Fig. 6), and a highly diverse, highly endemic benthic fauna existed, which generally had low abundances. Subsequently, a pronounced lateral facies differentiation existed across the basin with clear-cut differences between a deep basinal, and a shallow platform facies; the benthic fauna was generally less diverse, with a high percentage of immigrants from other regions and with generally higher abundances (Hints *et al.* 1989). Our own data support these earlier assumptions. Taxon occurrences in Estonian outcrops reveal significantly decreased diversities and increased abundances in post-Keila stages (Fig. 8), and the diversity of dominant groups reef builders is lower in post-Keila reefs.

Ainsaar et al (2004) coined the term ‘Middle Caradoc Facies and Faunal Turnover Event’ for this interval and considered it as ‘one of the most important faunal change horizons in the post-Tremadocian’, and Dronov & Rozhnov (2007) drew at the Keila/Oandu boundary the line between their climatic interpretation of the Baltic sediments as temperate versus tropical. Likewise, the interval may be described as a major change in the mode of carbonate production across the basin. From the earliest Katian onward a very characteristic facies of pure carbonate mudstone occurs in a wide area in the more proximal regions of the basin (calcilutites in the terminology of e.g. Jaanusson, 1982, aphanitic limestone in the Estonian and Russian literature e.g. Raukas & Teedumäe, 1997, Baltic limestone, and lithographic limestone in e.g. Spjeldnaes & Nitecki, 1994, and *Ostseekalk* in the German literature e.g. Hucke, 1967). This facies is poorly fossiliferous except of strongly recrystallized calcareous green algae (Spjeldnaes & Nitecki, 1994). Typical examples are the Slandrom Limestone (Calner *et al.* 2010*a*) of central Sweden, the Rägavere, Saunja and Moe Formations of northern Estonia (e. g. Hints *et al.* 2005), and the Östersjö Limestone (Axberg, 1980), and File Formation (Bergström et al, 2004) in the Bothnian Sea and subsurface Gotland respectively. Mud mounds occur at the aphanitic limestone facies and reefs are common in the more proximal parts of the extension area (Fig. 6). Basinwards this carbonate mudstone/bioherm facies rapidly fades out and only within a zone of c. 50 km, intercalates with argillacous limestone-marls. The Baltic limestone facies and the bioherms must be considered as two aspects of one and the same Late Ordovician very gently dipping rimmed carbonate platform, which started to develop during the earliest Katian. What were the causes for the development of this new mode of carbonate production, and what were the controlling factors?

5. b. Causes of reef/mound formation in the Baltic Basin

5.b.1. The palaeogeographical migration of Baltica and a changing tectonic regime

Baltica became an independent palaeocontinent during the Ediacarian (570–550 Ma) and collided with Laurentia during the Late Silurian (420–400 Ma) (Roberts, 2003, Cocks & Torsvik, 2005). The Ordovician history of this palaeocontinent was shaped by a northward drift from low to high, near equatorial palaeolatitudes and the docking of Avalonia at the terminal Ordovician (c. 443 Ma) (Cocks & Torsvik, 2005). The drift is interpreted as a changing influence of rifting and converging plates with a steady closure of the Iapetus Ocean in palaeo-NW, and the Törnquist Ocean in palaeo-SE of the Baltic Basin.

The drift and the changing tectonic regime had a substantial influence on the sedimentation and the faunal composition of the region with cold-water sediments and faunas early, and temperate to tropical elements late in the Ordovician (e.g., Cocks & Torsvik, 2005, and papers in Servais & Harper, 2013). Hence, major changes within the benthic fauna during the critical Sandbian/Katian boundary involved an increased influx of taxa from Avalonia and Laurentia (Hansen & Harper, 2008; Hansen *et al.* 2009). Moreover, the general diversity trend of Baltoscandia with a Sandbian peak (Hammer, 2003) and a Katian decline (termed ‘Katian prelude’ of the Hirnantian extinctions by Kaljo *et al.* 2011) was interpreted as a consequence of Baltica‘s drift through latitudes with optimal climatic conditions during the Kukruse-Keila stages.

However, Baltica's drift was a steady gradual movement (Cocks & Torvik, 2005) and the faunal change and the establishment of a new facies pattern was, in geological terms, a sudden process. Currently, the explanations for the processes that led to these rapid changes remain largely on speculation and more detailed investigations are needed to reconstruct processes of faunal change and systemic turning points.

The moving plate tectonic setting of Baltica had an influence on the depositional situation of the Baltic Basin. Increasing Late Ordovician subsidence rates suggest a gradually increasing lithospheric flexure (e.g., Poprawa *et al.* 1999; Sliaupa *et al.* 2006; Sliaupa & Hoth, 2011). The main causes behind this flexure are assumed to be the amalgamation of Avalonia, and the closure of the Iapetus Ocean. However, the published subsidence curves (e.g., Poprawa *et al.* 1999; Sliaupa *et al.* 2006, Artyushov *et al.* 2008; Sliaupa & Hoth, 2011) substantially vary over different parts of the basin without any basin-wide punctuated changes at the Sandbian/Katian boundary. Seismic profiles across the central and northern Baltic Basin reveal a fault controlled syndepositional sea floor morphology with late Katian mound structures partly following N/S directed fault lines (Tuuling & Flodén, 2000). But this local pattern does not explain the specific timing of the reef development it does not explain the spatial pattern of the reef/mound girdle in its entirety, and it provides no explanation for the development of a strictly limited platform with carbonate mudstone. Hence, the palaeogeographic shift of Baltica and the changing tectonic regime had a major effect on the background situation of the scene, but other processes, such as e.g. a shift in the oceanographic condition, must have been influenced the initiation and development of large-scale reef development.

5.b.2. Sea level as a controlling factor

The abundance of recorded reef and mound occurrences differs over the individual Late Ordovician time intervals with a concentration in intervals with generally low sea levels (Fig. 9). The oldest interval with concentrated reef/mound occurrences is the interval spanning the time immediately before the onset of the GICE through the rising limb of the GICE during the earliest Katian. Throughout Baltoscandia, the reef and mound facies unequivocally occurs directly below the major unconformity / erosion surface at the Oandu Stage base (Fig. 7). In the lake Mjøsa area (Norway) and in the Vasalemma area (Estonia), the reefs and their lateral equivalent beds generally represent a depositional environment that is shallower than the underlying facies

(Opalinski & Harland, 1981; Kröger *et al.* 2014a, b). This is in conflict with general assumptions that reef and mound growth requires substantial accommodation space and thus must have climaxed during a transgressive interval. This inconsistency is reflected in interpretations of the sea level history of this time interval. In the scheme of Dronov *et al.* (2011) the earliest Katian reef succession represents the uppermost part of depositional sequence VII of Dronov *et al.* (2011). In contrast, in the scheme of Nielsen (2004) the succession spans a number of drowning (DE) and lowstand events (LE) (from base to top: Keila Drowning Event, Frognerkilen LE, Nakkholmen DE, and Solvang LE).

The conflicting interpretations are best explained as a result of different scaling of the events in which the depositional sequences of Dronov *et al.* (2011) represent third order eustatic cycles, whilst the events of Nielsen (2004) reflect higher order cycles. Herein, the earliest Katian growth of the reefs and mounds are interpreted as reflecting short-term (higher than third order) transgressive episodes within a generally regressive long-term (third order) regime.

A similar situation can be reconstructed for the concentrations of reefs in sediments representing the time immediately before the onset of the HICE – rising limb of the HICE during the earliest Hirnantian. The reef bearing Hirnantian strata again are shallower than the underlying beds, and the reefs in turn occur directly below the major Hirnantian erosional unconformity (Kröger *et al.* in press; Hints *et al.* 2000). Hence, the general depositional setting was under a regressive regime, whilst the reef growth climaxed in a period of intermediate sea level rise that created the required accommodation space.

This latest Sandbian / earliest Katian and early Hirnantian concentration of reefs in periods just before major sea level falls represents either a primary signal and is directly related to processes triggering the formation of the bioherms, or it is an effect of preservation. The latter is likely because only those reefs and mounds are preserved in the today's incomplete ancient landscape, which were formed in the deeper, today still existent parts of the basin. It is conceivable that the existent reefs in the region reflect only a fraction of a much more proliferous proximal platform facies with a much higher reef density, which today is eroded away. In fact, some evidence supports this hypothesis:

(1) A general picture from outcrop and drill core data emerges with shallow, echinoderm/bryozoan/stromatoporoid/tabulate patch reefs in isolated proximal

regions, and with green algal/sponge rich stromatactis mud mounds in deeper parts of the basin. In Estonia the shallow patch reefs are concentrated in locally restricted areas that are limited onshore of the erosional front of the Baltic Klint (Vasalemma Limestone reefs, Moe Formation reefs, Adila Formation reefs). In all likelihood more reefs grew in the now eroded more proximal parts of the platform.

(2) In Gotland the Pirgu Stage mounds are distributed along the northern edge of the present extension area of Pirgu Stage sediments. Mounds of the older Rakvere–Nabala stages occur predominantly southwards, that is basinwards, of the younger Pirgu Stage mounds (Bergström *et al.* 2004), and the oldest mud mounds, time equivalent to the Kullsberg Limestone of the Keila Stage, occur even further south in an area E of Öland, Sweden (Flodén, 1980). This distribution is consistent with scenarios of a gradual Katian sea level rise until a climax during the regional Vormsi Stage and a subsequent sea level fall (e.g., Harris *et al.* 2004; Dronov *et al.* 2011). It is highly likely that a similar northward shift paced by a slowly rising sea level also occurred in shallow water reefs. Shallow water reefs younger than Keila Stage are preserved only in very restricted areas in northern Estonia and Norway. It is very likely that reefs developed further onshore during most of the Katian and parts of the Hirnantian, and that these reefs were eroded already during the latest Hirnantian. Major evidence of Hirnantian subaerial emergence and erosion can be found in seismic profiles (Tuuling & Flodén, 2000, 2010) and on top of the Boda Limestone mounds in central Sweden (Kröger *et al.* 2015). Hence, the concentration of reefs and mounds in times of low sea level simply may be an effect of the better preservation potential of the more basinal structural positions of these reefs and mounds. Nevertheless, an interdependence of preservational factors with primary factors for reef/mound development must be assumed, because the sea level fundamentally controlled the depositional environment. The sea level also influenced the specific current regime, and with it ecological properties such as local sea water oxygenation, temperature, nutrient availability, and sediment load.

5.b.3. Climate as a controlling factor

Improvements of the interregional stratigraphic resolution allow for unprecedented detail in the reconstruction of Late Ordovician climatic changes. This is especially the case for the Sandbian/Katian boundary interval. A series of major K-bentonites in the relevant time interval (e.g.,. Kinnekulle, Deicke, Millbrig, K-bentonites) can now precisely be dated by U-Pb zircon ages and placed in a high resolution temporal framework (Bauert *et al.* 2014; Sell *et al.* 2013, 2015). Additionally, an increasing number of sections is available with geochemical data that record the latest Sandbian / earliest Katian GICE interval, which is a useful tool for precise interregional correlation (e.g., Young *et al.* 2008; Ainsaar *et al.* 2010, Bergström *et al.* 2010*a, b, c*; see above).

In Baltoscandia the GICE interval coincides not only with the first record of shallow water reefs, but also with a low diversity period of organic-walled microfossils (Kaljo *et al.* 1996), and with a dramatic faunal turnover within a wide variety of faunal groups (Meidla, 1996; Ainsaar *et al.* 1999, 2004). The later part of the GICE interval (falling limb of this stable isotope event in the δ_{13}C curve) records a short term basin-wide major change from a carbonate-dominated sedimentation toward a siliciclastic-dominated sedimentation within a transgressive regime (Ainsaar *et al.* 2004).

These perturbations are not restricted towards Baltoscandia. Time equivalent environmental change is known also from North America. Over the vast area of the Appalachian Basin and the US Midcontinent the GICE interval marks a rapid transition from tropical type to temperate type carbonates (Lavoie, 1995; Holland & Patzkowsky, 1996; Patzkowsky *et al.* 1997; Pope & Steffens, 2003; Ettenson, 2010). The changes in the sedimentary regime coincide with marked changes in faunal composition and evolutionary dynamics (Holland & Patzkowsky, 1996; Patzkowsky *et al.* 1997; Wright & Stigall, 2013). Similar changes within local sedimentary and faunal regimes globally provide compelling evidence for a perturbation of the global carbon cycle and a significant global cooling during the GICE interval (e.g., Patzkowsky *et al.* 1997; Saltzman & Young, 2005; Young *et al.* 2008; Calner *et al.* 2010*a*, *b*; Rosenau *et al.* 2012; Pancost *et al.* 2013).

The first appearance of widespread reefs and mounds in the Baltic Basin at the Keila/Oandu boundary can be effortless connected with these global events (e.g., Kröger *et al.* 2014a, b). However, at this time a detailed analysis does not exist in which the growth of the shallow reefs of, e.g., the Vasalemma and Mjøsa formations and the coeval mud mounds of the Kullsberg Limestone would be traced back to specific changes in palaeoceanographic properties such as nutrient availability, oxygenation, and water temperature.

A better palaeoceanographic data record exists for the younger Pirgu Stage interval in which reefs and especially mud mounds developed in abundance across large parts of

the Baltic Basin. This interval is termed 'Boda Event' after the prominent mud mounds in the Boda Formation of central Sweden. Fortey & Cocks (2005) originally gave this label to a 'short-lived episode of global warming' before the Hirnantian glaciation. In its original sense, the event was rather a long time interval spanning the base of the *Dicellograptus complanatus* Graptolite Zone to base of the Hirnantian entire (see discussion in Kröger *et al.* in press). Taken literally as the time interval of the formation of the Boda Limestone mounds (and also of the formation of the mounds in central Estonia) the event would range from the early Pirgu-early Hirnantian stages (*Dicellograptus anceps* - *Metabolograptus extraordinarius* graptolite zones), a time interval with a length of nearly 3 Ma (according to Cooper *et al.* 2012).
The initiation and climax of the formation of the Pirgu Stage mud mounds are interpreted as reflecting a relatively stable late Katian episode with high eustatic sea levels, and well-oxygenated, oligotrophic, cool waters entering the Baltic Basin from palaeo-North (Kiipli *et al.* 2009; Kröger *et al.* in press., and references therein). In contrast, the terminal beds of the Boda Limestone mounds and of the Võhma mound of central Estonia developed during conditions of general sea level fall, and less well-oxygenated, and warmer bottom level temperatures (Kröger *et al.* in press). This interpretation agrees well with Melchin *et al.*'s (2013) review of the 'Boda event' as an interval comprising an early and late Boda warming, and a mid Boda cooling. In this scheme, the late Katian climax of reefs and mound formation would correspond with at least two subsequent episodes of Late Ordovician cooling and an intermediate phase of warming. This demonstrates that the highly variable Katian – Hirnantian climatic conditions alone are a poor predictor for reef and mound growth within the Baltic Basin.

5.b.4. Biotic factors

A number of biotic factors potentially influence the timing and extend of the bioherm formation on Baltica. Two important biotic factors are (1) the taxonomic composition of its main constructors, and (2) the resilience of the organismic consortia that formed the individual bioherms.
(1) The foundation and expansion of specific types of bioherms relies on the evolutionary range and radiation of its main constructors. The key taxa in Ordovician reefs and mounds of Baltica are bryozoans, echinoderms, green algae, sponges,

stromatoporoids, and tabulate corals. A coincidence of an evolutionary first appearance of these groups with first appearances of specific reef and mound types in Baltica could indicate a causal relation between the two.

However, reef constructions with encrusting bryozoans (Cuffey, 2006; Cuffey *et al.* 2013), with root-like holdfasts of rhombiferans and crinoids (Alberstad *et al.* 1976; Toomey & Nitecki, 1979, p. 43;), with sponges, stromatoporoids, and tabulate corals (e.g., . Webby *et al.* 2004; Nestor & Webby, 2004; Webby, 20042013) are known from Early and Middle Ordovician strata and older than any Baltoscandian reef. Likewise, the two dominant orders of siphonous green algae, the crown groups Bryopsidales and Dasycladales, had their initial diversification during the Floian, and Sandbian, respectively (Nitecki *et al.* 2004; Verbruggen *et al.* 2009).

Hence, the appearance of reefs and mounds in the Baltic Basin does not coincide with the evolutionary appearance of its main constructors. Similar types of reefs and mounds existed already during the Middle Ordovician. The main phases of Ordovician reef evolution and diversification took place earlier during the Middle Ordovician and the first half of the Sandbian Stage and the centres of these diversifications were elsewhere in lower latitudes (Webby, 2002).

Instead, the beginning of the growth of bioherms in Baltoscandia falls within a time interval, which was characterised by a global expansion of reef occurrences and by a further geographical and bathymetrical differentiation of reef associations (Webby, 2002). Baltica, in all likelihood, entered the geographical zone of reef growth at palaeolatitudes < 25°S when the main events of the Ordovician reef diversification were bygone (see also Webby, 2002), and the begin of the reef development in Baltica was dictated mainly by its paleogeographical shift.

(2) Biotic factors potentially played a major role for the stability of the reef development during the Late Ordovician. Ecological stability in reef ecosystems is predicted by reefal species diversity (Kiessling, 2005). Species richness in reef environments is negatively correlated with change in ecological parameters over the entire Phanerozoic (Kiessling, 2005). Accordingly, the diversity of reef ecosystems generally promotes the stability of the system itself. Evidence for a similar effect can be detected also in reefs and mounds of the Baltoscandian Ordovician.

The general Ordovician diversity curve for Baltica describes a bell shape reaching maximum diversities for all major groups during the late Sandbian / early Katian Keila Stage and showing a subsequent Late Ordovician diversity decrease (Hammer, 2003; Hints *et al.* 2010; Kaljo *et al.* 2011). The diversity of reef and mound assemblages contrasts with this Baltoscandian Late Ordovician trend of diversity decrease and remained stable or even increased. In a comparison of Late Ordovician diversities from collections of the entire present day Estonia with the diversity patterns in specific reef settings this decoupling becomes most evident (Fig. 8). During the Late Ordovician the Baltic reef environments became increasingly taxonomically diverse.

Our review demonstrates that shallow water reef and deeper water mud mound environments became a constant component of the Baltic Basin during the Late Ordovician. The bioherms had a fundamental impact for the geometry of the carbonate platform within the Baltic Basin and its vicinity. The relative stability of the bioherm environments throughout the entire Late Ordovician probably was enhanced by its an increasingly diverse faunal inventory. In a future analysis of evolutionary rates of the Baltic reef and mound this hypothesis can be tested.

6. Conclusions

The late Keila Stage (latest Sandbian/ earliest Katian) marks the beginning of a long-lasting period on Baltica with a widespread development of reefs in shallow and mud mounds in deeper epicontinental settings. Reefs and mounds persisted in the Baltic Basin probably with only little interruption during the late Hirnantian crisis until the latest Silurian (Flodén *et al.* 2001; Tuuling & Flooden, 2010). The start of the widespread growth of bioherms was accompanied with the establishment of a clear-cut facies differentiation into proximal nearly pure lime-mudstone, the so-called Baltic Limestone, and more argillaceous deeper deposits. At the same time, within an interval of no more than 1 Ma, the faunal assemblages of the basin changed substantially towards generally less endemic taxa and higher taxic abundances. The reasons for this early Katian turnover and the subsequent relative stability are complex.

1. Probably the main determining factor for the timing of the start of the Baltic bioherm development was the large-scale tectonic movement of the palaeocontinent from initially high southerly palaeolatitudes in the early Ordovician towards palaeotropical latitudes in the Late Ordovician. The latitudinal shift was accompanied by an increasing tectonic stress, initial Caledonian movements in the palaeo-NW and

the docking of Avalonia in palaeo-SE, which led to gradually increasing lithospheric flexure in the region of the Baltic Basin. The punctuated depositional and faunal changes during the early Katian indicate a rather rapid establishment of a new ecological status quo probably by crossing a biogeographical boundary. A detailed analysis of the facies and faunal changes is needed to develop this hypothesis further. The currently available data suggest that the entry of Baltica in a geographical zone that allowed for a widespread bioherm formation was a major factor for the Sandbian radiation of reefal and reef related organisms such as stromatoporoids, corals, pelmatozoans, bryozoans, and siphonous green algae.

2. The current spatiotemporal distribution of bioherms is a result of interdependent factors of relative seal level and climate during the time of deposition. The likelihood that bioherms are preserved from long time erosion is higher when deposited during low sea level in deeper parts of the basin. At the same time, oceanographic conditions were more favorable during times of cooler global climates, low sea level and glacial episodes because of enhanced marine circulation, upwelling and oxygenation. The first appearance of widespread reefs and mud mounds on Baltica coincides with a period that is considered to be the onset of a long-lived glaciation during the Late Ordovician, the GICE interval. It is likely that the event triggered the reef and mound growth on Baltica, but a detailed palaeo-oceanographical analysis is currently not available to further test this hypothesis.

3. The subsequent Late Ordovician establishment of a reef and mound environment on Baltica was originally interpreted as the ‘Boda Event’, named after the prominent mud mounds in the Boda Limestone Formation of central Sweden. The growth of individual mounds in the Boda Limestone and in time equivalent mounds elsewhere lasted over a period of more than 3 Ma from the late Katian well into the early Hirnantian stage. This time interval records substantial climatic changes, changes in relative sea level, in oxygenation level and in clastic sediment load of the covering water column. Climatic factors and subsidence levels alone do not explain the surprisingly stable reef and mound development during this time.

4. Biotic factors poorly explain the initiation of the Late Ordovician reef and mound growth in the Baltic Basin, but evidence exist that the once established ecosystems developed a robust resiliency against changing physicochemical disturbances. The local diversity trajectories of mound and reef environments increased during the Katian/Hirnantian, which is in discrepancy with the generally declining Late

Ordovician diversities across Baltica. Further studies are needed to test the hypothesis of an increasing resilience and stability.

In summary, these four points underline the need of further palaeo-ecological and palaeo-oceonographic studies for a better understanding of the dynamics of Ordovician diversification processes. The stratigraphic resolution, the tools for data compilation and analysis are existent and an increasing repertoire of geochemical analyses available to solve the problems.

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Table 1. Genus diversity estimates and results of occupancy modeling of genera. n_{occs}, number of occurrences; r_{obs}, observed richness; S_{rare}, rarified diversity; SSQS, subsampled diversity after Shareholder Quorum Subsampling (Alroy 2010); $n_{sites}/n_{collections}$, number of sites and collections ('replicates') used for occupancy modeling (see methods section); mean naive occ., mean naïve occupancy is the mean proportion of number of genera per sample / total number of genera; p_{det}, detection probability give probability of a genus detected in sample.

Sample	n_{occs}	r_{obs}	S_{rare} (+-95%conf.int.)	S_{SQS}	$n_{sites}/n_{collections}$	**mean naïve occ.**	p_{det} (+-95%conf.int.)
Estonia, Pirgu Stage	2398	227	64(+-4)	94			
Estonia, Moe Fm., Pirgu Stage	583	72	35(+-3)	26	6/18	0.11	0.34 (0.14-0.61)
Estonia, Nabala Stage	247	48	35(+-2)	27	4/9	0.14	0.41 (0.15-0.74)
Estonia, Rakvere Stage	2357	153	41(+-4)	35	11/29	0.06	0.41 (0.16-0.73)
Estonia, Oandu Stage	1709	181	60(+-4)	75	19/101	0.02	0.38 (0.16-0.63)
Estonia, Keila Stage*	3799	269	59(+-4)	90	32/294	0.02	0.12 (0.06-0.23)
Estonia, reefs Ärina Fm., Porkuni Stage	787	103	51(+-4)	51			
Estonia, Vasalemma Fm., Keila Stage	1134	347	46(+-4)	48			
central Sweden, Boda Lst, Pirgu-Porkuni Stage	672	206	84(+-4)	173			
central Sweden, Kullsberg Lst, Keila Stage	130	47	-/-	-/-			

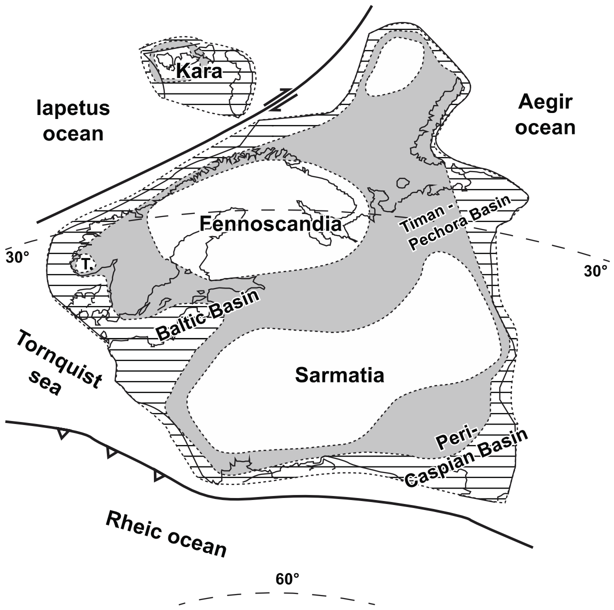

Figure 1. Palaeogeographic reconstruction of the Baltica palaeocontinent during the Late Ordovician (modified from Cock & Torsvik 2005).

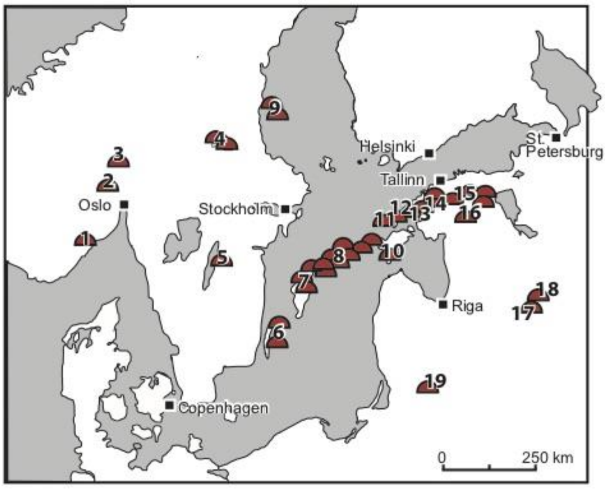

Figure 2. Map of Baltoscandia with Ordovician reef and mound locations discussed in text. 1. Steinvika Fm., Skien-Langesund area; 2. Ullerntangen, Tyrifjorden; 3. Mjøsa Fm., Nes-Hamar; 5. Kullsberg Fm., and Boda Fm., Lake Siljan district; 5. subsurface Östergotland; 6. subsurface E Öland; 7. subsurface Gotland; 8. subsurface central Baltic; 9. subsurface Bothnian Sea; 10. subsurface Saaremaa Island; 11. subsurface Vormsi Island; 12. Hoitberg & Niibi, Moe Fm.; 13. Ruunavere, Moe Fm.; 14. Vasalemma Fm; 15. Ärina Fm.; 16. Võhma and Jõgeva, Pirgu Stage; 17. Ludze, Adila Fm.; 18. Malta, Adila Fm.; 19. Pamituvys, Pirgu and Porkuni Stage.

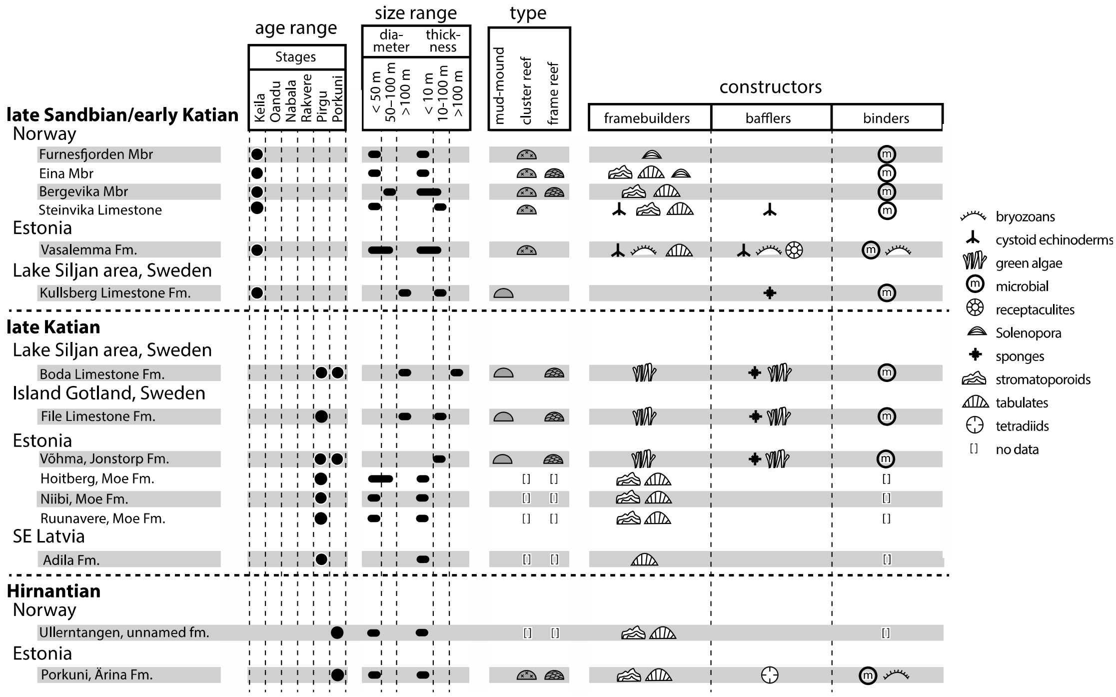

Figure 3. Overview of characters of main Ordovician reef and mound occurrences, note the widespread role of microbial binders in all better known localities. See also Fig. 4. Fm., Formation.

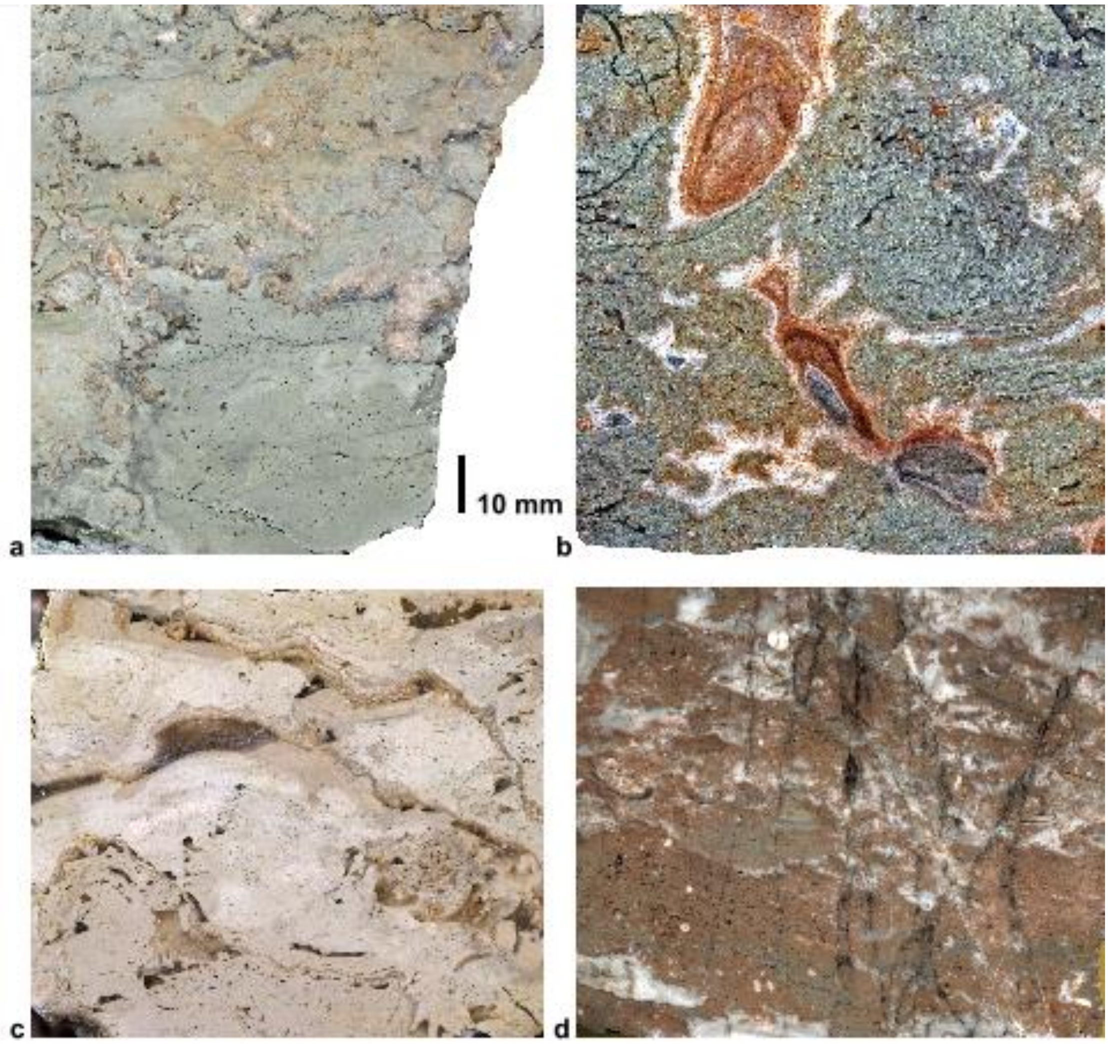

Figure 4. Examples of core limestones of selected Ordovician mud mounds and reefs. All samples are mainly composed of a mosaic of fenestral microbial wackestone to mudstone and patches of allochthonous wackestone. The reefs differ in containing a substantial amount of bryozoans and/or echinoderms, which functioned as sediment binders. A. Vasalemma Formation, late Sandbian / early Katian, Nordkalk quarry Vasalemma, Estonia, with synsedimentary cave filling (spicule rich mudstone) with ramose and encrusting bryozoans. B. Võhma mud mound, late Katian, Võhma drillcore, Estonia with large stromatactis cavities filled with multiple generations of cement. C. Siuge Member, Ärina Formation, Hirnantian, Porkuni, Estonia, with encrusting bryozoans.

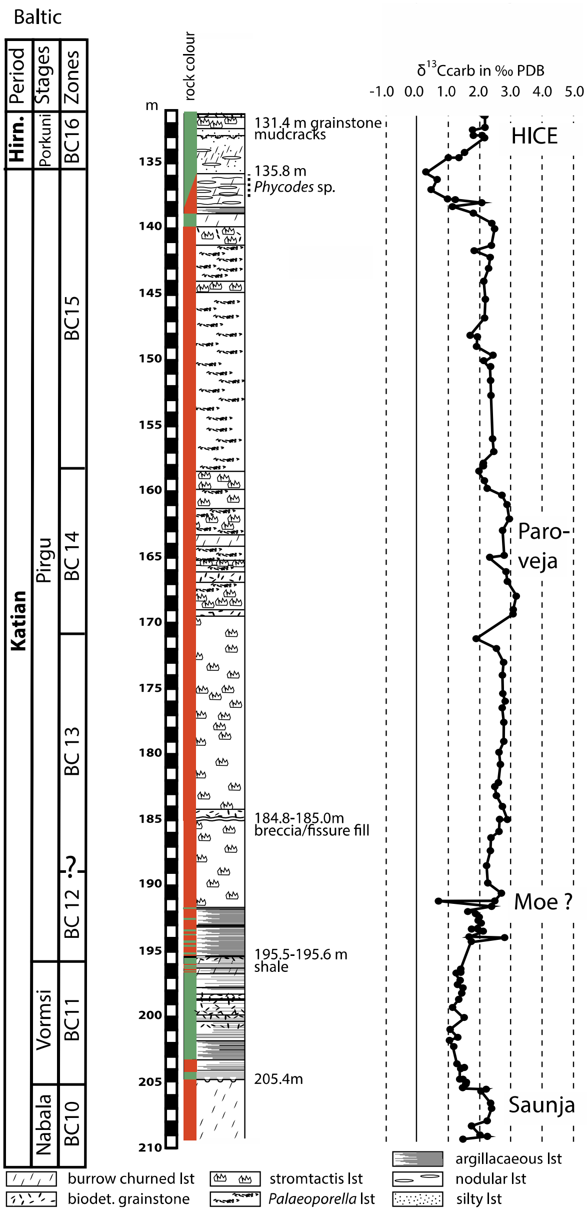

Figure 5. Part of the Võhma drill core section, central Estonia (58.612260°N, 25.559460°E), depicting the lithology and chemostratigraphy of a more than 50 thick *Palaeoporella* reef/mud mound nearly time equivalent to the Boda Limestone mounds in Central Sweden. Abbrevations: BC, Baltic Carbon Isotope Zones of Ainsaar *et al.* (2010); biodet., biodetritical; Hirn., Hirnantian; lst, limestone.

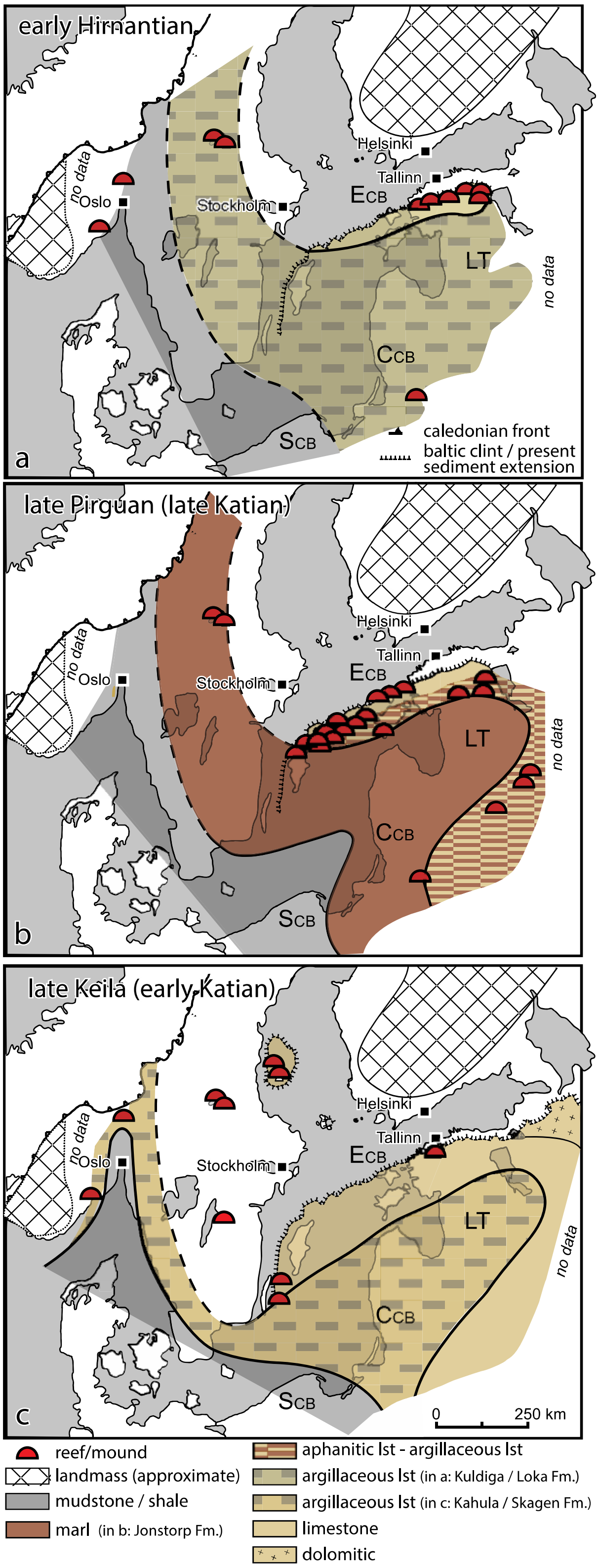

Figure 6. Facies reconstructions of Baltic region of three selected time slices with reef occurrences. Note the high facies differentiation during the Pirgu and Hirnatian stages. A. based on Hints & Meidla (1997*b*), Hints *et al.* (2010), Hints *et al.* (2000)), Kiipli (1997), Männil (1966), Oraspõld (1975), Paškevičius (1997); B. based on Hints *et al.* (2005), Kröger *et al.* (2014*a*), Männil (1966), Modliński & Szymański (1997),

Paškevičius (1997), Tuuling & Flodén (2000). C. based on Ainsaar *et al.* (2004), Bergström *et al.* (1997, 2004, 2011*a*), Bockelie (1978), Dronov & Dolgov (2005), Flodén (1980), Grahn & Nõlvak (2007), Hints & Meidla (1997*a*), Jaanusson (1979), Modliński & Szymański (1997), Winterhalter (1972). Positions of Finnish mainland from Männil (1966), and Uutela (1998), and from Telemark land from Hansen (2011). Abbrevations: LT, Livonian Tongue, CCB; Central Baltic Confacies Belt; SCB, Scanian Confacies Belt, after Jaanusson (1976).

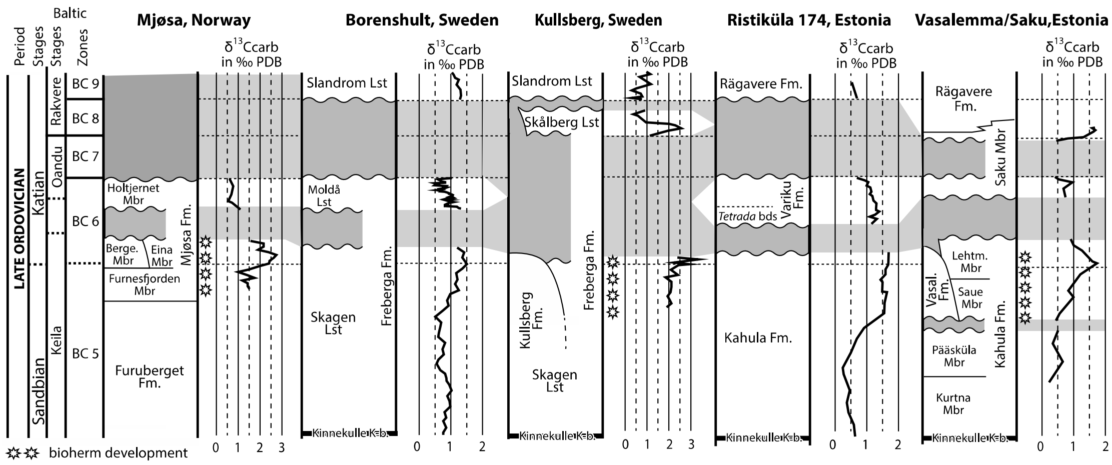

Figure 7. Correlation scheme of late Sandbian / early Katian interval of selected sections of Baltoscandia, depicting depositional gaps. The Sandbian / Katian boundary is based on Bergström *et al.* (2012), but see Sell *et al.* (2015). Our correlation differs from that of Bergström et al (2011*b*) in placing the Skålberget and Moldå limestones of Borenshult in a position that is slightly younger, nearly time equivalent to the Holtjernet Member of the Mjøsa Formation. In contrast, Bergström *et al.* (2011*b*) correlate the entire Freberga Formation of Dalarna, Sweden (inclusively Skålberget and Moldå limestones) with the lower and middle members of the Mjøsa Formation. Our new interpretation is based on the correlation of the discontinuity surfaces at the base of the Moldå Limestone and similarities in the $\delta_{13}C$ curve. The relative height of the lithostratographic units does not relate to the thickness of sediments but was fit to the relative timescale. Hiati are marked as gray intervals (for method of correlation see text), reef and mound growth with stars. Note the time equivalent occurrence of reef and mound growth at Sandbian/Katian boundary interval. $\delta_{13}C$ data of are Mjøsa area from Bergström *et al.* (2010*b*, 2011*b*), Borenshult from Bergström *et al.* (2012), Kullsberg from Calner *et al.* (2010*b*); Ristiküla from Ainsaar *et al.* (1999), Vasalemma from Kröger *et al.* (2014*a*, *b*). Abbrevations: Berge., Bergevika; K-b., K-bentonite; Mbr, Member; Fm., Formation; Lst, Limestone; Vasal., Vasalemma.

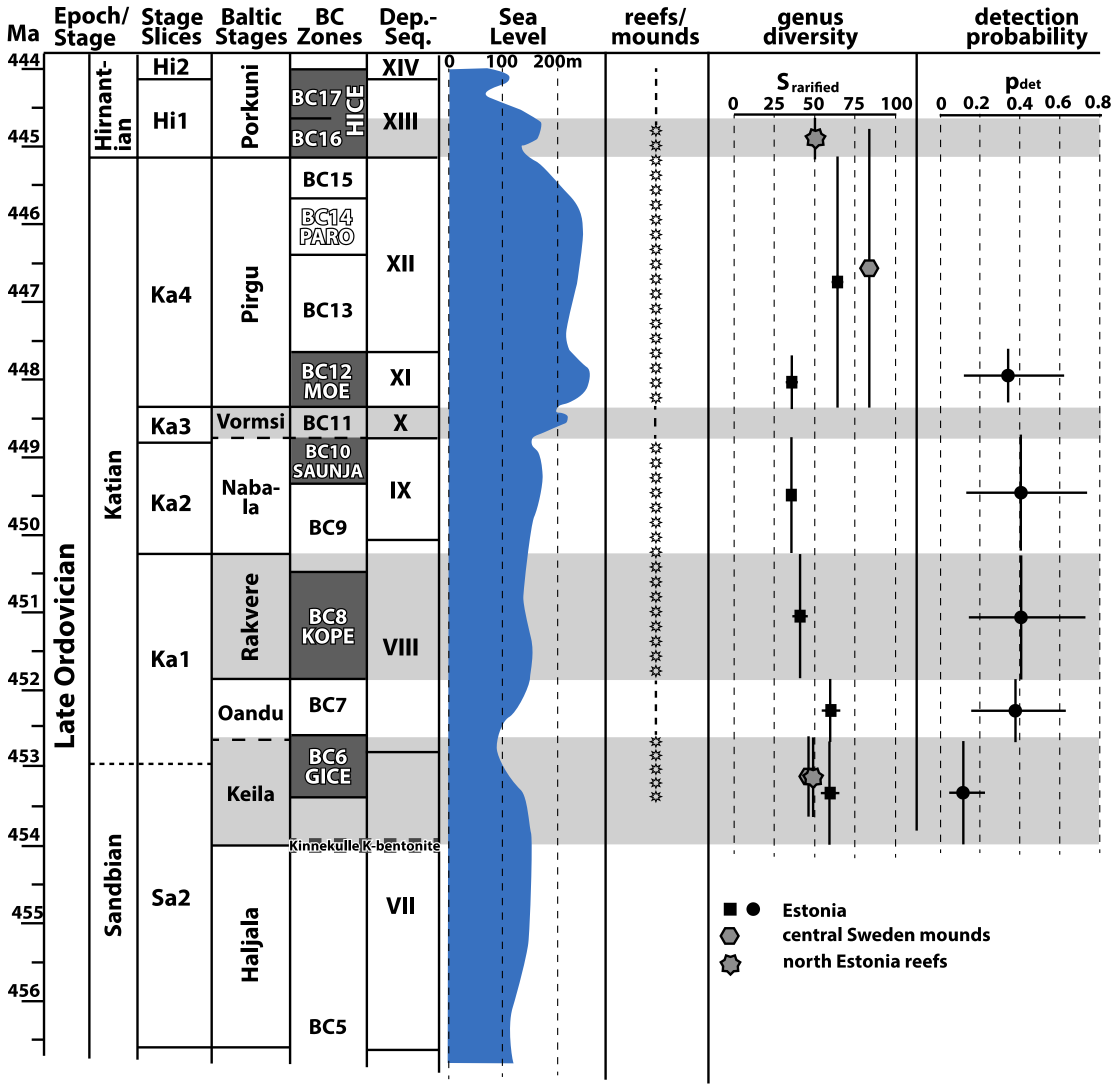

Fig. 8. Diversity estimates and detection probabilities of the Late Ordovician of Baltoscandia compared to the sea level curve of Dronov *et al.* (2011). Note the general decrease in diversities and the strong increase in detection probabilities after the Sandbian in the Estonian samples. Note also the increasing diversity trends in the reef and mound samples. Diversity values from Estonia are based on occurrences in the geocollection database SARV of the Keila Stage (exclusive Vasalemma Formation), the Vasalemma Formation, the Oandu Stage (exclusive Vasalemma Formation), the Oandu, Rakvere, Nabala, and Pirgu stages, the Moe Formation, and the Ärina Formation, lower Hirnantian (see Table 1). Genus diversity estimate is calculated by rarefaction with quota n=130 (Kullsberg Limestone sample). Detection probability was calculated based on occupancy modeling (see methods section). Detection probability is the probability of a genus occurrence within a site and can be

interpreted as proxy for genus abundance, see methods. Samples from Estonia reflect stage levels, and additionally one sample from the Pirgu Stage Moe Formation. Samples from north Estonian reefs are from Vasalemma Formation, Keila Stage, and Ärina Formation, Porkuni Stage. Samples from Central Sweden are from Kullsberg Limestone (Keila Stage), and Boda Limestone (Pirgu-early Hirnantian). Abbrevations: BC., Baltic Carbon Isotope Zones of Ainsaar *et al.* (2010); Dep.-Seq., depositional sequence; GICE, Guttenberg isotope carbon excursion; HICE, Hirnantian isotope carbon excursion; KOPE, Kope or Rakvere isotope carbon excursion; MOE, Moe isotope carbon excursion; PARO, Paroveja isotope carbon excursion; SAUNJA, Saunja isotope carbon excursion.

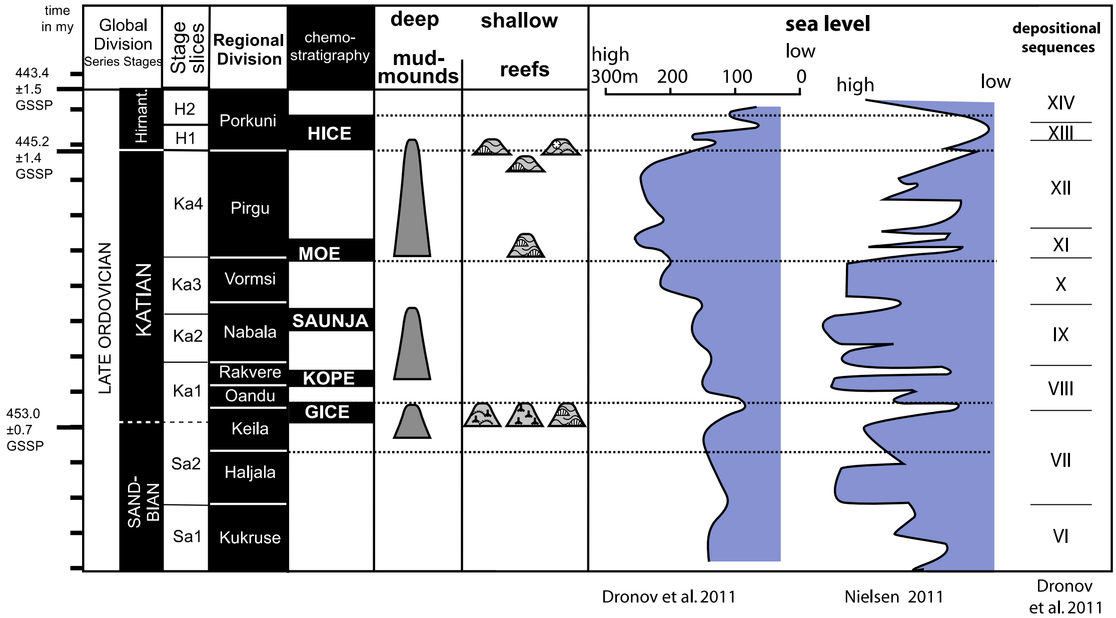

Fig. 9. Overview of reef / mound development within Baltoscandia compared to regional sea level interpretations and depositional sequences. Note the concentration of shallow reefs in regressive intervals. Absolute timescale from Cooper *et al.* (2012). Abbrevations: GSSP, Global Boundary Stratotype Section and Point. For symbols see Fig. 3.